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**Metallic Materials with High Structural Efficiency**

**DYNAMIC RECRYSTALLIZATION  
OF LOW STACKING FAULT ENERGY METALS**

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## Outline

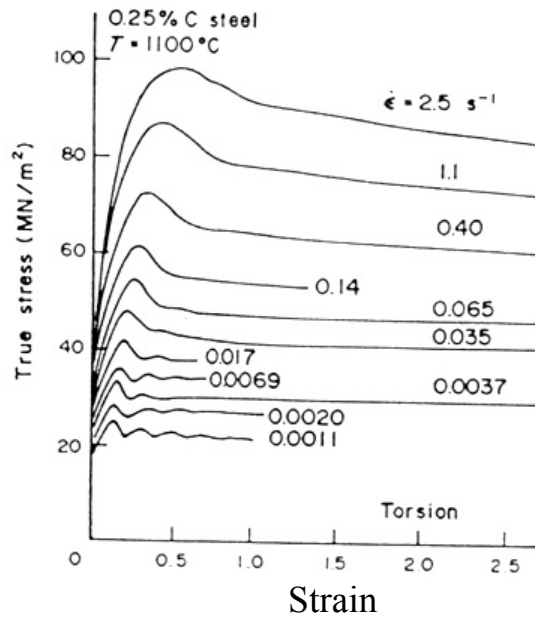
- Continuous and discontinuous dynamic recrystallization (DRX)
- DRX in a high purity base austenitic stainless steel
- DRX in a 718 grade nickel base superalloy. "Continuous nucleation"
- Conclusions

## Continuous vs. discontinuous dynamic recrystallization

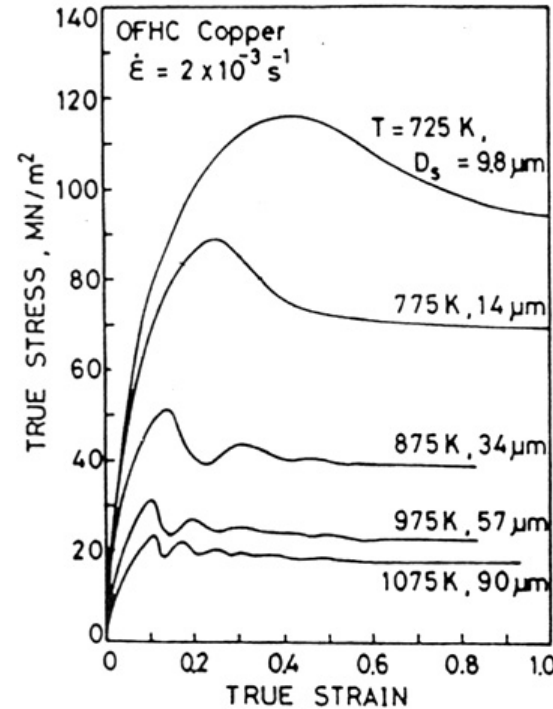
<b>DDRX</b> or "classical" DRX	<b>CDRX</b> or "rotation", "apparent", "in situ" DRX, or "extended dynamic recovery"
occurs by local (rapid) cycles of strain-hardening → nucleation → growth of new grains	occurs by progressive (slow) transformation of subgrain boundaries (LAGB) into grain boundaries (HAGB)
- dynamic recovery is weak	- dynamic recovery is strong (dislocation rearrangement and annihilation)
- dislocation densities are inhomogeneous (strong $\Delta\rho$ )	- dislocation densities are homogeneous (weak $\Delta\rho$ )
- the rate of grain boundary migration is high	- the rate of grain boundary migration is low
low stacking fault energy materials: Cu, $\gamma$ -iron and austenitic steels, Ni-base superalloys, ...	high stacking fault energy materials: Al, $\alpha$ -iron and ferritic steels, $\beta$ -titanium, ...

DDRX: transition from multiple peak (low Z) to single peak (high Z) DRX

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right)$$



[Rossard & Blain, 1959]



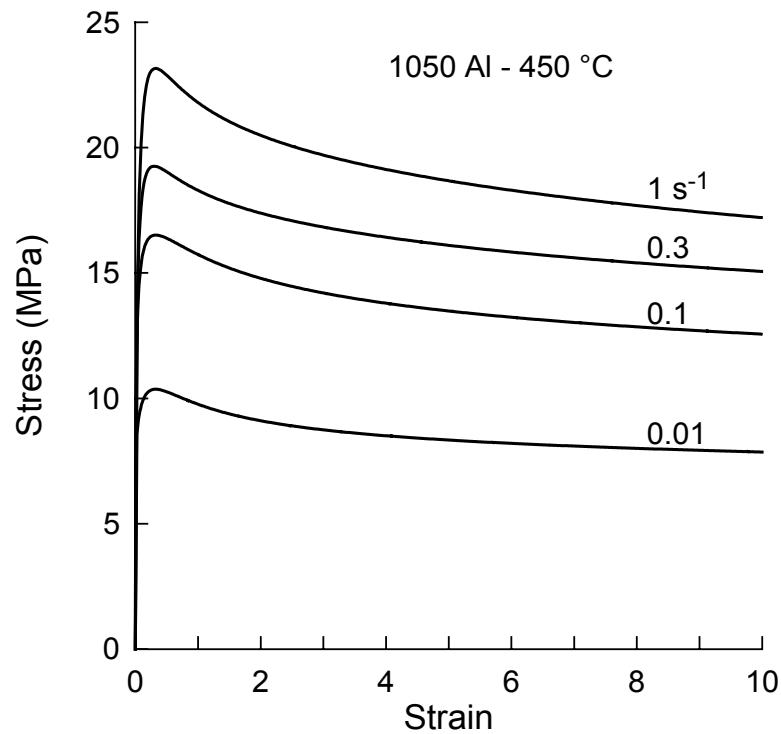
Grain refinement

Increasing Z

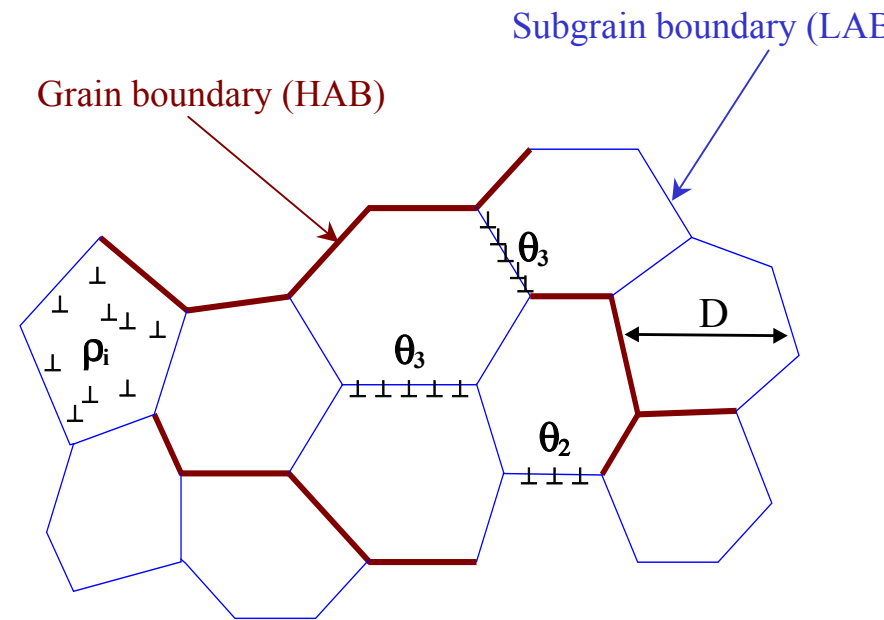
Grain growth

[Blaz et al., 1983]

## CDRX: "Smooth" stress-strain curves

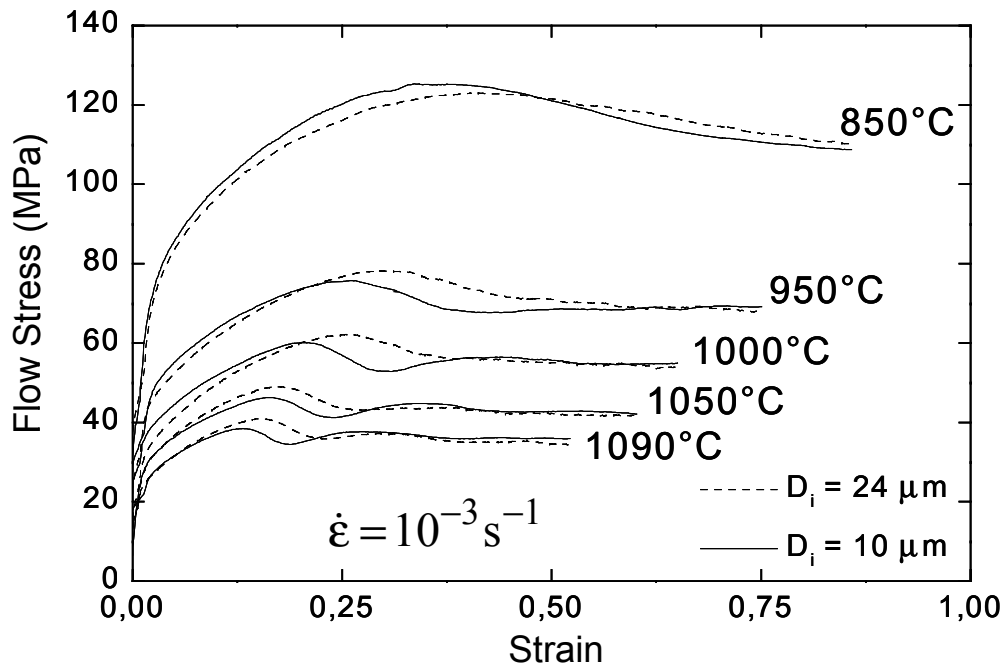


## Schematic representation of the CDRX crystallite microstructure



[Gourdet & Montheillet , 2003]

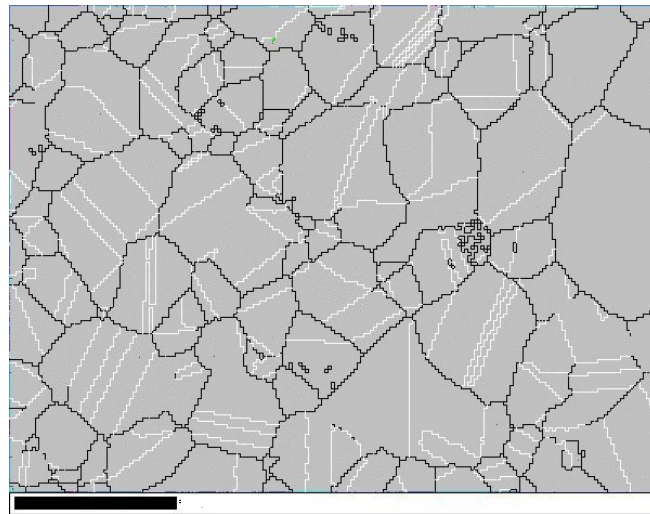
DRX in a high purity base austenitic stainless steel  
close to the A304 grade (18 %Cr, 12.2 %Ni, 15 ppm C, 10 ppm S, and 10 ppm N)  
[Gavard, 2001]



$Q \approx 400 \text{ kJ/mol}$

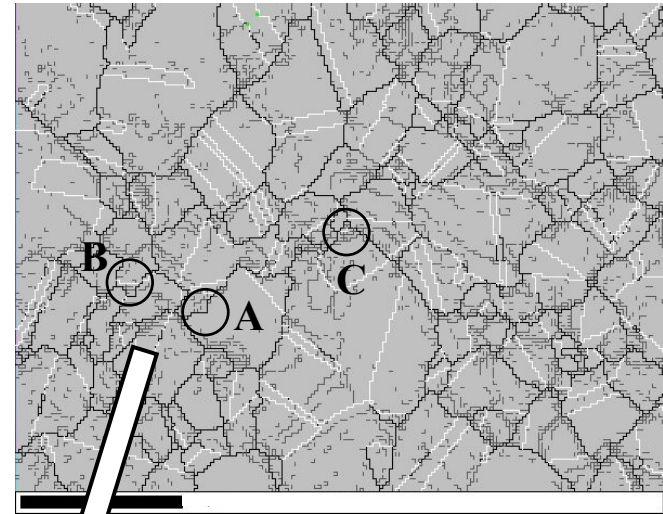
Multiple to single peak transition  
 $Z \approx 10^{13} - 10^{14} \text{ s}^{-1}$

## Microstructural changes – 850 °C, $10^{-3} \text{ s}^{-1}$

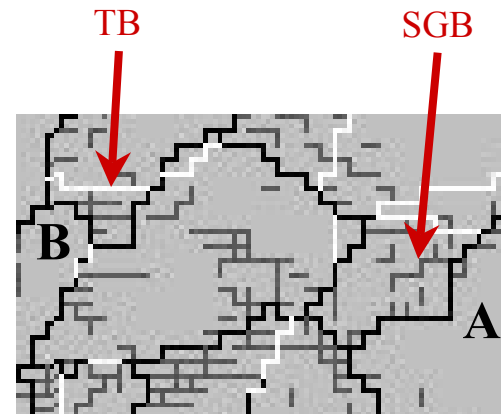


50  $\mu\text{m}$

initial state



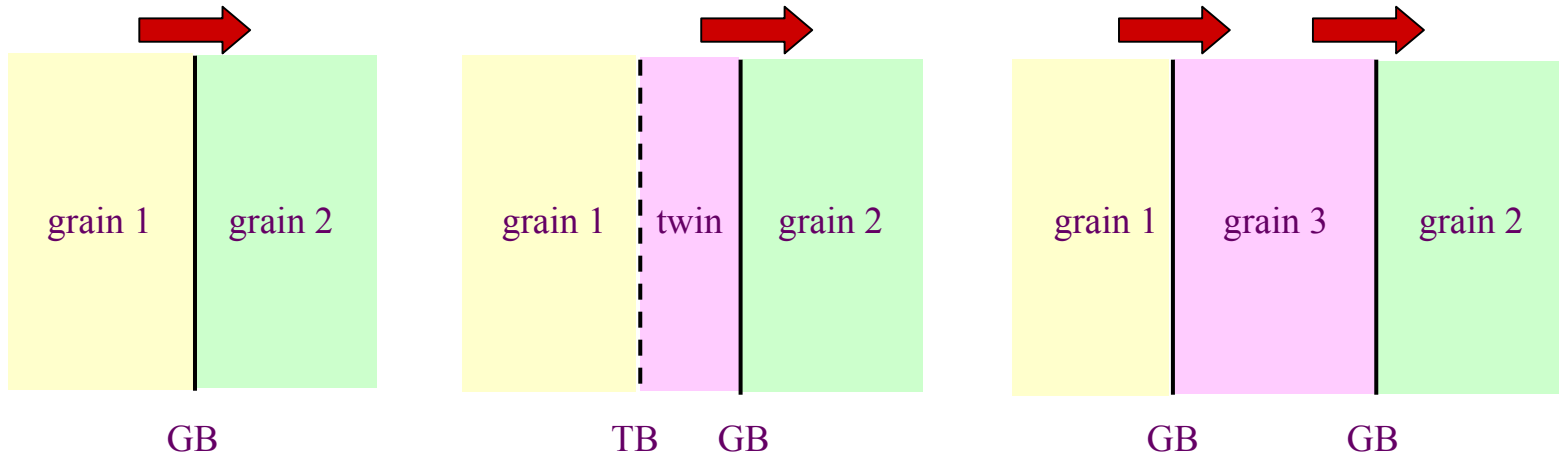
$\epsilon = 0.1$



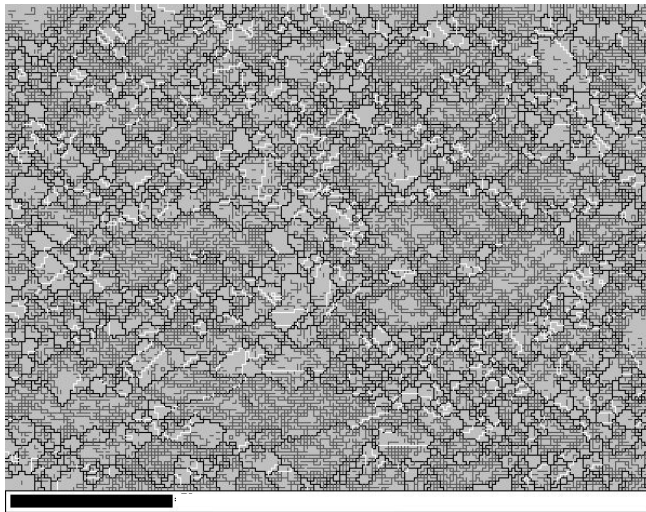
Nucleation by  
(initial) grain boundary bulging  
and (growth) twinning

## Nucleation by (growth) twinning

increasing time and strain →



## Microstructural changes (cont'd)

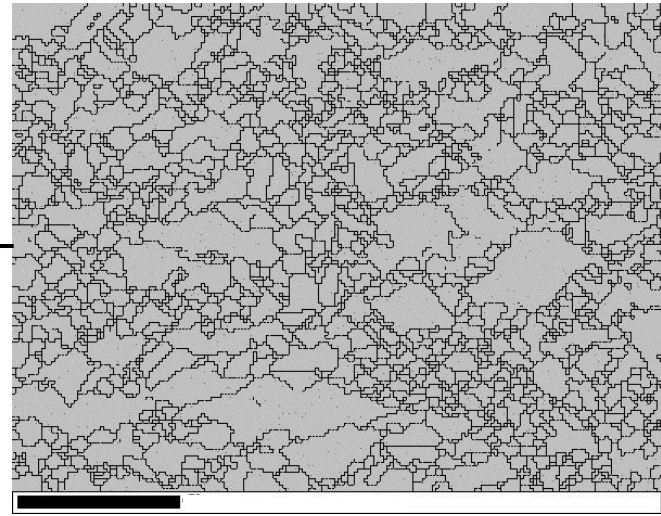


50 μm

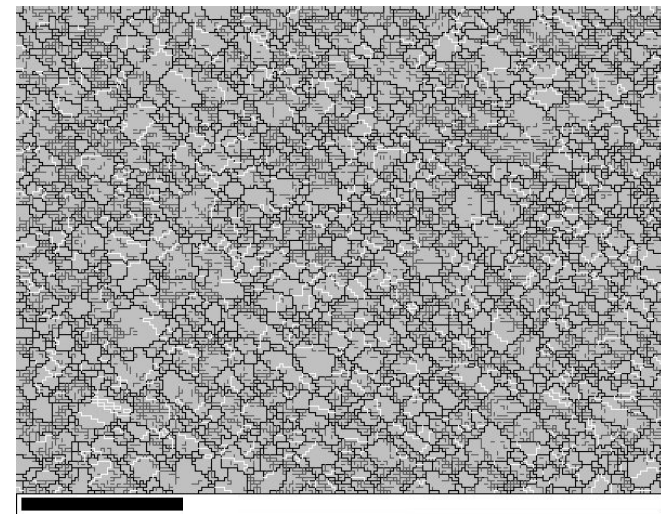
$\varepsilon = 0.7$

Necklace DRX

Mixture of "young" and "old" grains



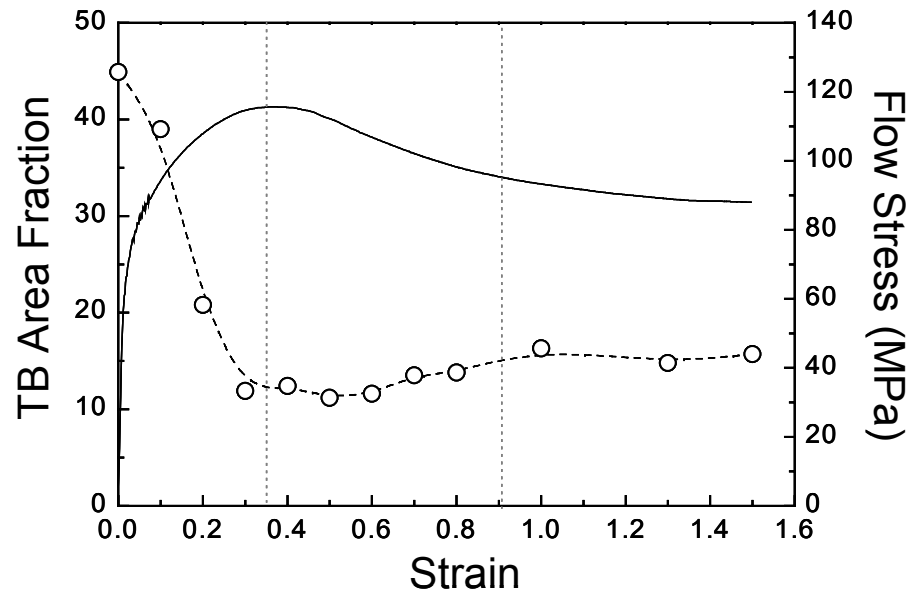
same area without SGB



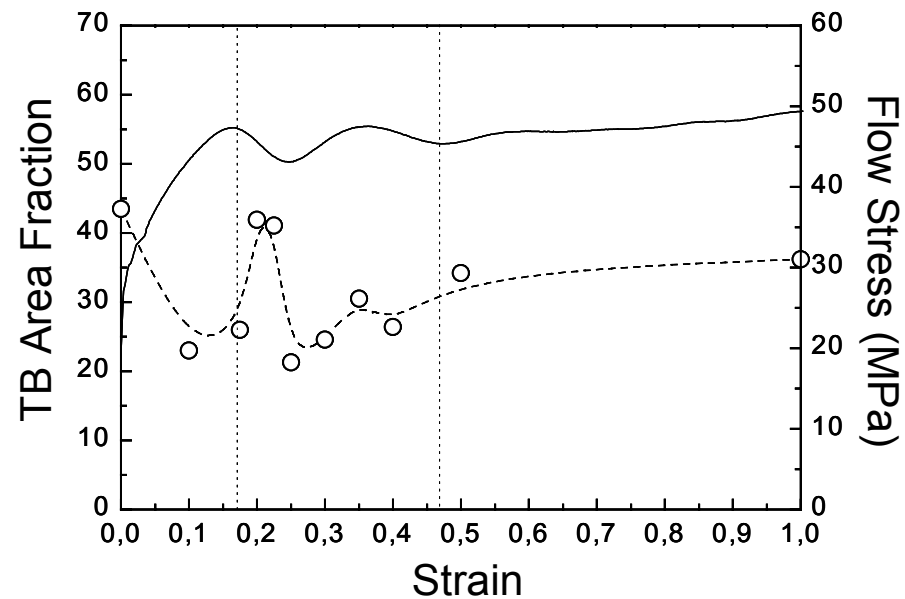
$\varepsilon = 1.5$  ( $\approx$  steady state)

## Evolutions of the twin boundary area fractions

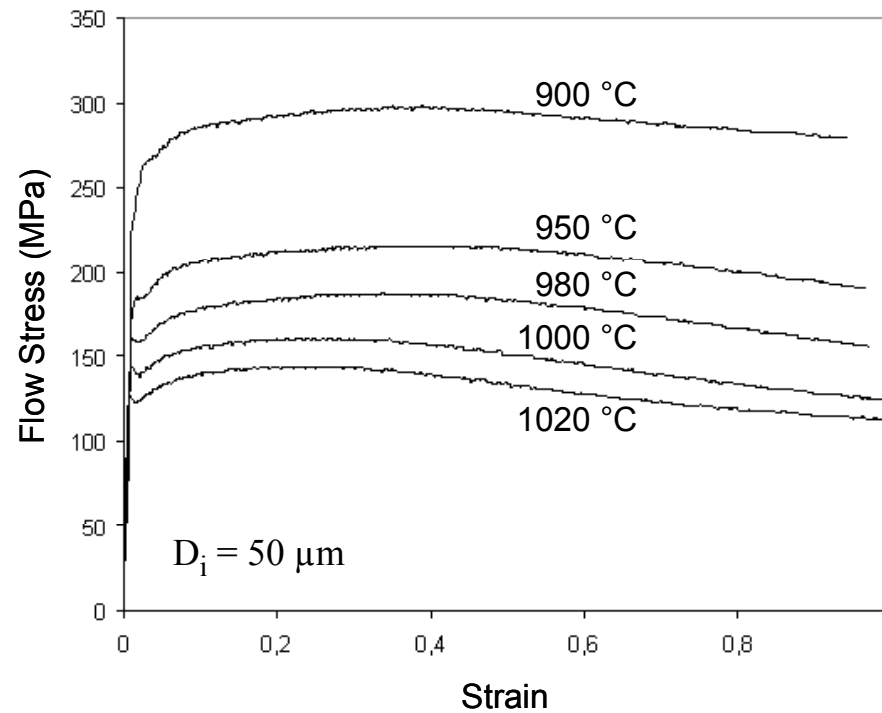
Single peak case  
(850 °C,  $10^{-3} \text{ s}^{-1}$ )



Multiple peak case  
(1050 °C,  $10^{-3} \text{ s}^{-1}$ )



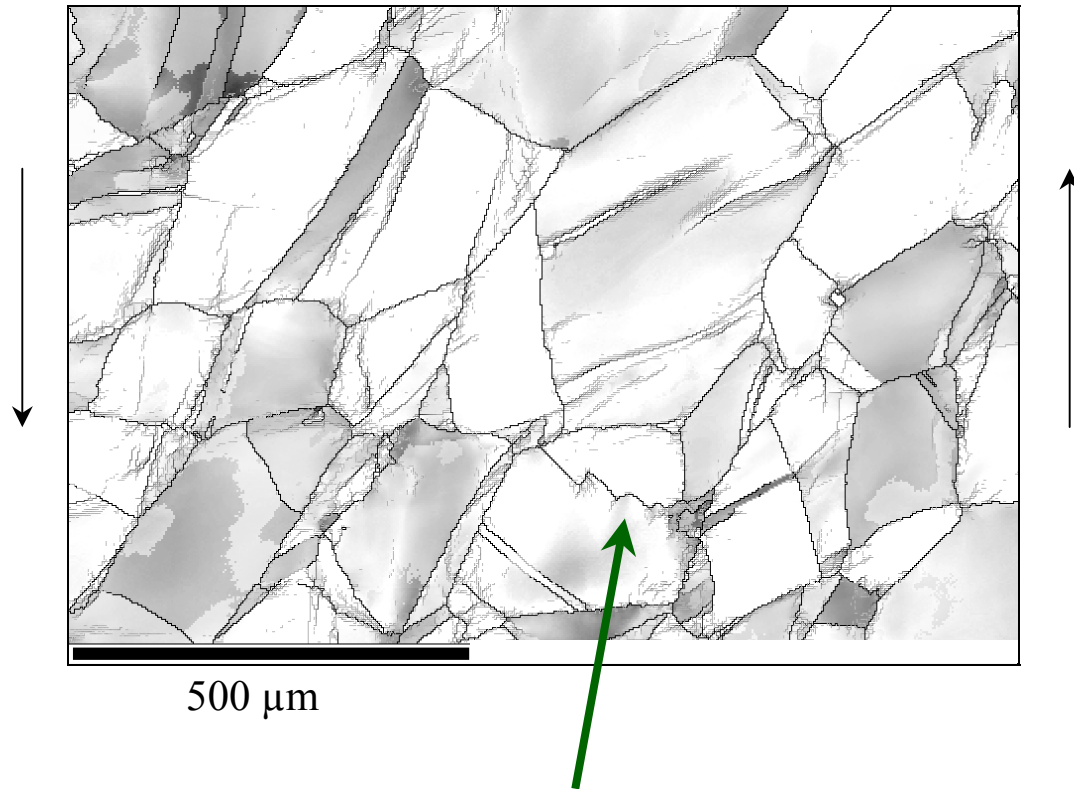
## DRX in a 718 grade nickel base superalloy (after solution treatment of $\delta$ Ni<sub>3</sub>Nb phase)



$Q \approx 400 \text{ kJ/mol}$

Single peak type  
Grain refinement

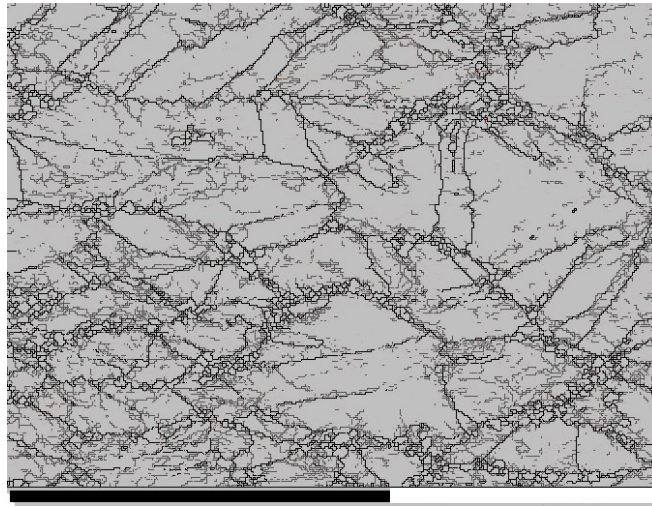
Fragmentation of the initial microstructure  
(torsion at 900 °C,  $= 10^{-2} \text{ s}^{-1}$ ,  $\epsilon = 0.4$ )



500 μm

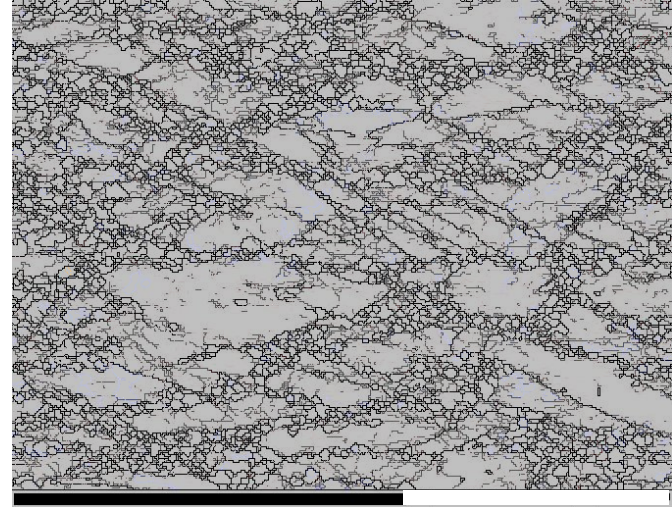
nucleation by (initial) grain boundary bulging

## Microstructural changes – 980 °C, $10^{-2} \text{ s}^{-1}$

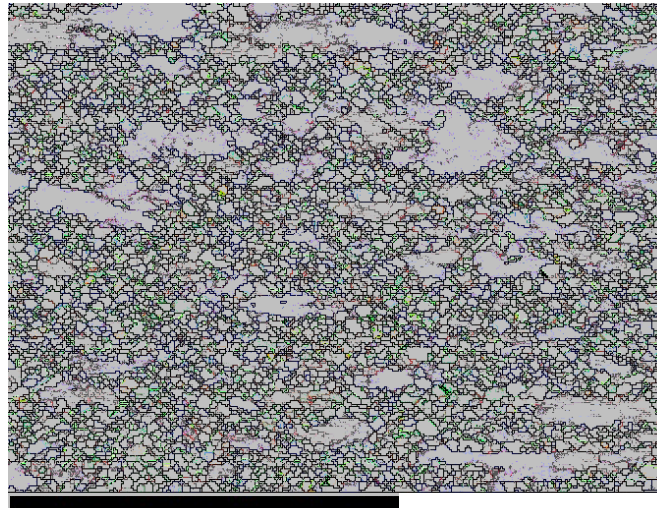


200  $\mu\text{m}$

$\varepsilon = 0.4$

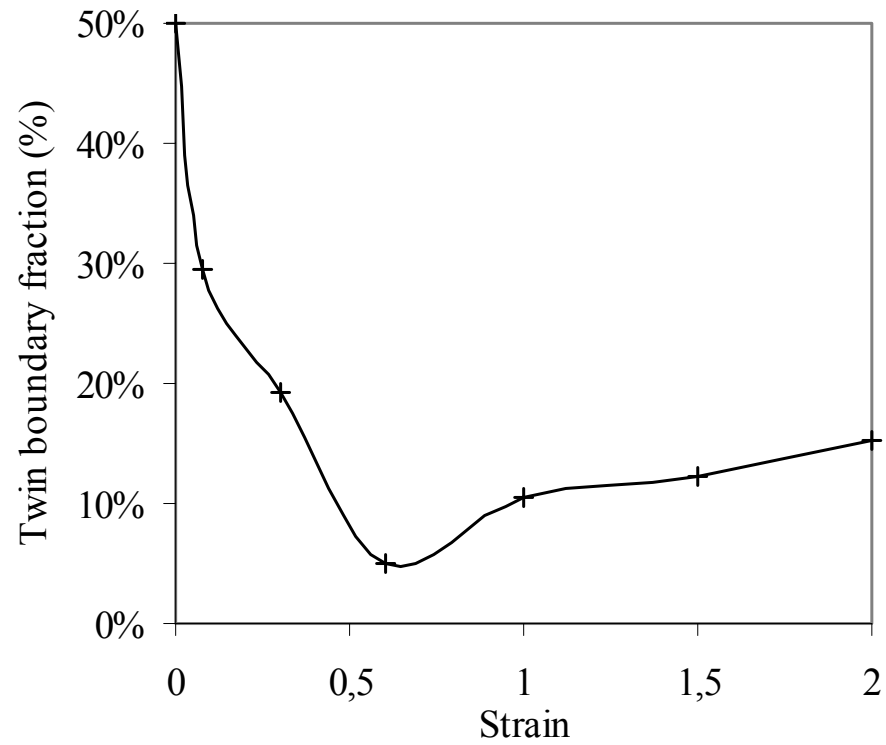


$\varepsilon = 0.7$



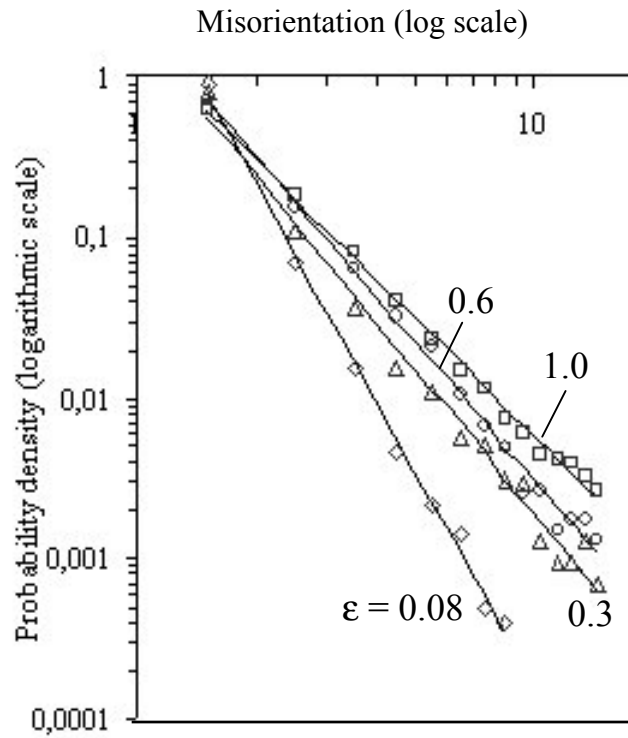
$\varepsilon = 1.0$

## Evolution of the twin boundary area fraction



nucleation by (growth) twinning

## Strain dependence of the subgrain boundary misorientation distributions



$$\varphi(\theta) = k \theta^{-q}$$

where  $q$  increases with strain

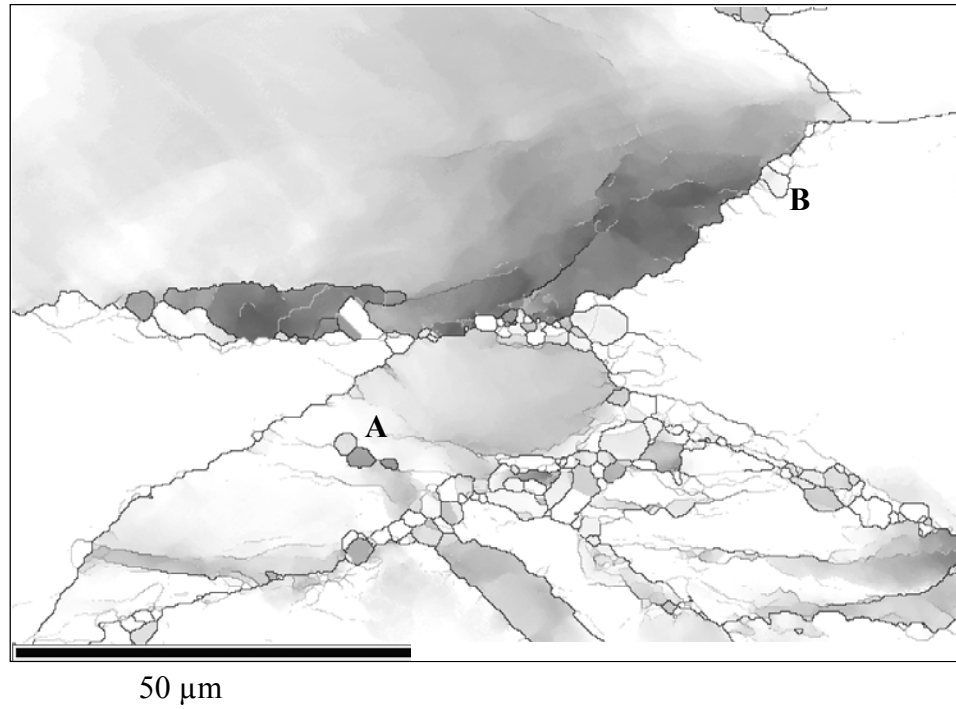
For the steady state ( $q = q_s$ ),

$$\varphi(\theta) \dot{\theta} = k \theta^{-q_s} \dot{\theta} = \text{constant}$$

$$\Rightarrow \dot{\theta}(\theta) = C \theta^{q_s}$$

(For Al alloys,  $q_s = 0$ )

## "Continuous nucleation" (A)



## Conclusions

- Discontinuous DRX in low stacking fault energy metals occurs with variable kinetics, e.g. much more slowly in 718 alloy than in 304 steel
- Nucleation of new grains takes place by three distinct mechanisms:
  - (initial) grain boundary bulging,
  - repeated (growth) twinning,
  - and, in alloy 718, "continuous nucleation", similar to CDRX
- Slower grain boundary migration rates in alloy 718 may be attributed to
  - smaller driving forces due to more efficient dynamic recovery,
  - grain boundary mobility reduced by niobium solutes
- Respective contributions of CDRX and DDRX in nickel base superalloys could be controlled by adjusting volume fractions of Nb or other addition elements